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# Can gravity play a role at the electroweak scale?[1]

J.J. van der Bij

*Albert–Ludwigs–Universität Freiburg, Fakultät für Physik*
*Hermann–Herder Str.3, 79104 Freiburg*

**Abstract**

A connection is made between a model for strongly interacting vector bosons and the spontaneously broken theory of gravity. The theory contains effectively no Higgs particle, but should have strong interactions at the electroweak scale. Some speculations about the nature of these interactions and possible experimental signatures are discussed.

The standard model for the weak interactions describes the presently existing data well. However, whereas the gauge-structure of the model has a simple geometrical interpretation, the Higgs part of the model is not particularly attractive. The Higgs sector is responsible for the existence of a large number of ununderstood parameters in the theory. Therefore it is a natural question to wonder whether the Higgs sector is fundamental. The existence

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of a fundamental Higgs sector is made even more questionable because of the so called naturalness problem.

The naturalness problem is the situation that the Higgs mass is quadratically divergent, after one takes radiative corrections into account. Therefore an ordinary scale for the Higgs mass would be the cut-off scale of the theory. However the Higgs mass is supposed to be of the order of the weak scale. Therefore a fine-tuning is necessary. Other questions involve the cosmological constant, implying a possible relation with gravity and the existence of a Landau pole where the theory breaks down. Altogether this has led to a number of proposals to eliminate or alter the Higgs sector of the theory.

One example is supersymmetry, which avoids the naturalness problem but leaves the other problems untouched [1].

Another way is technicolor where all interactions are gauge interactions and the symmetry breakdown appears spontaneously. However no realistic model has been constructed [2].

A third alternative, to cancel the quadratic divergences within the standard model itself [3], led to the related idea of topquark condensates [4]. Also here no realistic model exists.

This leads to the fourth logical alternative, that the cut-off of the theory is indeed at the weak scale and that strong interactions among the vector bosons should exist. Experimentally little is known about the self-interactions among the vector bosons. At $\bar{p}p$ colliders direct limits on the vectorboson anomalous magnetic moment and quadrupole electric moment have been reported [5]. Indirect limits on the anomalous couplings via radiative corrections as measured at LEP are cut-off dependent and do not constrain these couplings severely. Even if three-vector bosons couplings are absent, this is not a very severe constraint, since strong interactions are in first approximation only to be expected at the level of the four vectorboson couplings. This is because only here one starts to become sensitive to the coupling among longitudinally polarized vector bosons, which by the equivalence theorem correspond to the Goldstone bosons of the theory. These Goldstone bosons form a direct probe of the Higgs sector of the theory. In practice it has therefore been difficult to construct models with strong interactions in the three vectorboson sector, whereas possibilities are present in the four vectorboson sector.

A case at hand is the class of models where one introduces extra fields, having strong interactions which via radiative corrections feed down to the vectorbosons themselves [6,7]. The example that is to be discussed here is the model of ref[6]. This is in many ways the simplest extension of the

standard model, containing only one extra singlet, coupling to the Higgs sector of the theory. The Lagrangian is given by:

$$\mathcal{L} = -\frac{1}{2}(D_\mu\Phi)^\dagger(D^\mu\Phi) - \frac{1}{2}(\partial_\mu x)^2 - \frac{\lambda_1}{8}(\Phi^\dagger\Phi - f_1^2)^2 - \frac{\lambda_2}{8}(2f_2 x - \Phi^\dagger\Phi)^2 + \mathcal{L}_{gauge} \tag{1}$$

The physical content of this theory consists of two Higgs fields that mix with one another. By a suitable choice of parameters one can generate a large mass splitting between the fields. When this is done the integration over the heavy fields leads to an effective Lagrangian giving large deviations even at lower energies. The condition for this to happen is that there should be a hierarchy of coupling constants in the theory. Otherwise the decoupling theorem is valid. In this model the condition is $\lambda_2 >> \lambda_1 >> 0$. Ignoring hypercharge, the strong effects can be summarized by the following effective Lagrangian :

$$\mathcal{L}_{eff} = \alpha_1 Tr(V_\mu V^\mu)Tr(V_\nu V^\nu) + \alpha_2 Tr(V_\mu V^\nu)Tr(V^\mu V_\nu) + g\alpha_3 Tr(F_{\mu\nu}[V^\mu, V^\nu]) \tag{2}$$

where

$$V_\mu = (D_\mu U)U^\dagger \tag{3}$$

and

$$F_{\mu\nu} = (\partial_\mu - \frac{ig}{2}\vec{W}_\mu\cdot\vec{\tau})\frac{\vec{W}_\nu\cdot\vec{\tau}}{2i} - (\mu \leftrightarrow \nu) \tag{4}$$

$U$ is the unitary matrix describing the Goldstone boson fields. Of particular importance is the parameter $\beta = 128\pi^2(\alpha_2 - 2\alpha_1)$, which is responsible for the formation of vector resonances. In the limit $f_2 >> f_1$ one simply has $\beta = \lambda_2/\lambda_1$. This shows that indeed $\beta$ can be made arbitrarily large. The presence of the extra interactions leads in general to resonances in the I=1 sector of the theory [8]. For large values of $\beta$ the resonances become narrower and lie at lower energy. Of course the $X$ field here is not to be considered as a fundamental field, but only as an effective description for an as yet unknown dynamical mechanism. In ref[6] it was implicitly assumed that the $X$ field had some relation with technicolor. We will not pursue this connection here, but study the possibility of a relation with gravity.

The reasons to assume a connection between gravity and the Higgs sector are manifold. First there is the question of the cosmological constant, which is generated by the Higgs potential. The second reason is that both gravity and the Higgs particle have some universal characteristics. Gravity couples universally to the energy-momentum tensor, the Higgs particle

to mass, which corresponds to the trace of the energy-momentum tensor. In the model of ref[6] there is a further similarity between the $X$ field and the graviton in the fact that they are both singlets under the gauge group. An interesting question in gauge theory is the choice of representations one should take. In the standard model there exists basically only the fundamental representation for the fermions and the adjoint for the vector bosons. Because they have no coupling to ordinary matter, singlet fields are not well constrained by experiment. Typically one can argue that they are absent from the theory, because they can have a bare mass term, which can be made to be of the order of the Planck mass, making these fields invisible. However one can take the attitude that all masses, including the Planck mass should be given by spontaneous symmetry breakdown. In this case there is a hierarchy of mass scales $m_P >> v$. In the spirit of ref[6] we will assume that this hierarchy is due to a hierarchy in coupling constants and not in vacuum expectation values of different fields. Given these similarities it is now natural to consider the $X$ field to be essentially the graviton. We therefore make the identification $X = c.R$ in the Lagrangian [1], where $R$ is the curvature scalar. With this identification the model is a higher derivative theory and as such not directly useful. We therefore make the low energy expansion ignoring the higher derivative terms. One is then left with the Lagrangian:

$$\mathcal{L} = \sqrt{g}(\xi \Phi^+ \Phi R - \frac{1}{2} g^{\mu\nu} (D_\mu \Phi)^+ (D_\nu \Phi) - V(\Phi^+ \Phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}) \qquad (5)$$

This is the spontaneous symmetry breaking theory of gravity, with the standard model Higgs as the origin of the Planck mass. The remnant of the originally very strong interactions in [1] is the parameter $\xi$, given by $\xi = 1/16\pi G_N v^2$. This model was recently discussed in [9]. The physical content of the model becomes clear after the Weyl rescaling $g_{\mu\nu} \rightarrow \frac{\kappa^2}{\xi v^2} g_{\mu\nu}$, giving the Lagrangian :

$$\mathcal{L} = \sqrt{g}(\kappa^2 R - \frac{3}{2} \frac{\xi v^2}{|\Phi|^4} (\partial_\mu |\Phi|^2)(\partial^\mu |\Phi|^2) - \frac{1}{2} \frac{v^2}{|\Phi|^2} (D_\mu \Phi^+)(D^\mu \Phi) - \frac{v^4}{|\Phi|^4} V(|\Phi|^2)) \qquad (6)$$

This theory is basically the standard model without Higgs-particle, as the Higgs coupling becomes of gravitational strength. It is therefore non-renormalizable and needs new interactions at the weak scale. The nature of these interactions is not clear and one can at the moment only speculate.

One possibility is that at the weak scale strong interactions are present between different subconstituents of fermions and vector bosons. The interactions betweeen these subconstituents should not be of the ordinary gauge type, as technicolor models appear not to work. An example of fundamentally different interactions could be some form of random dynamics. The signature of such dynamics at lower energies is not particularly clear. It appears likely, that some set of pseudo Goldstone bosons could be present. These pseudo Goldstone bosons would not necessarily form a symmetric manifold, but chiral dynamics should still be valid. Preliminary investigations [10] show, that this scenario gives no problems with corrections to the $\rho$ parameter. Constraints from other LEP data are being studied. High energy colliders should have no problems seeing such pseudo Goldstone bosons.

A second possibility that fits in well with the idea that there is a Higgs gravity connection is the possibility of the existence of extra dimensions, the Kaluza-Klein models. For ordinary Kaluza-Klein models towers of states appear, which can be detected at future colliders. Normally one speaks here of the TeV scale; I want to emphasize here that such states could appear already at the weak scale. Higher dimensions could also show up in a different form. If the geometry of the extra dimensions plays a role in the dynamics, it is in principle possible that extra dimensions are being created in the process of the collision. These extra dimensions are not necessarily compact. The signature in this case is missing overall energy and momentum inside the detector, but not missing $p_T$. In the design of detectors one should take this possibility into account. For hadron colliders this signature would be rather difficult, as one does not know the energy of the incoming partons. Only a careful study of distributions could possibly give an answer here. For high energy electron-positron machines the situation is much better, while one in principle knows the energy of the incoming particles. A fully hermetic detector is needed however.

As a final possibility maybe gravity itself already starts playing a role at the weak scale. The presence of a zero in the metric is generally taken to be a place where quantum gravity plays a role. A zero in the metric corresponds to a zero in the Higgs field here, i.e. when the energy density of the Higgs field is of the order of 250 GeV. At first sight the creation of a coherent state with $\Phi = 0$ appears to be a process of infinitesimal probability. At the tree level one needs $O(m_P/v)$ Higgs particles each with gravitational coupling strength to be made. Because the theory is nonrenormalizable however, this may be a misleading conclusion as there is the very strong coupling $\xi$ present. Therefore higher loop effects could be much more important than the tree

level ones. This is the region of strongly coupled quantum gravity. A clue to what might happen is given, when one takes the analogy between [1] and [5] seriously. One has $\beta = O(m_P^2/v^2)$. This corresponds to vector resonances with a mass of $O(v^2/m_P)$, a form of composite anti-gravity. Possibly such particles may play a role in cosmology or in the missing mass problem. To make further progress along these lines one should have a formulation of quantum gravity, that allows one to study strong couplings like $\xi$. As such a formulation is lacking, presumably one has to look for some form of effective Lagrangian for gravity that could at least phenomenologically describe the dynamics. What form such an effective Lagrangian should take is not clear at present.

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